Regolith Volatile Recovery at Simulated Lunar Environments

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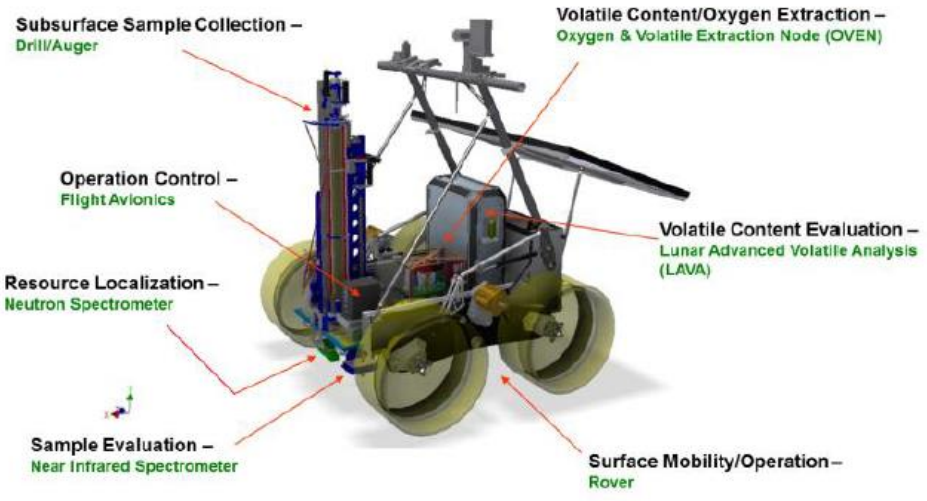
Lunar Polar Volatiles

- Permanently shadowed craters at the lunar poles contain water, ~5 wt% according to LCROSS
- Interest in water for ISRU applications
- Desire to 'ground truth' water using surface prospecting
  - e.g. Resource Prospector & RESOLVE
- How to access subsurface water resources and accurately measure quantity
  - Excavation operations and exposure to lunar environment may affect the results



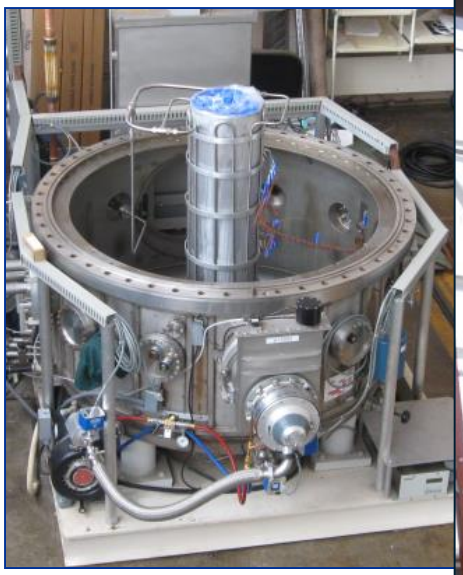
Volatile capture tests

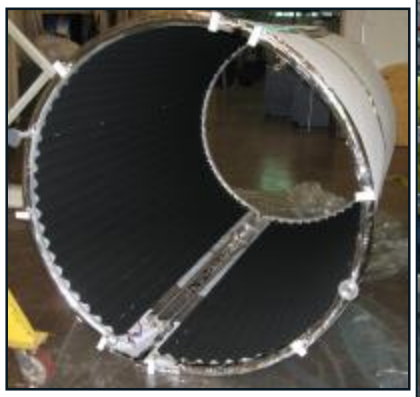
- A series of ground based dirty thermal vacuum tests are being conducted to better understand the subsurface sampling operations
  - Sample removal and transfer
  - Volatiles loss during sampling operations
  - Concept of operations
  - Instrumentation
- This presentation is a progress report on volatiles capture results from these tests with lunar polar drill prototype hardware
  - Previous data published at this conference last year
  - New data in 2015 from two test series
    - Honeybee Robotics Auger w/ RESOLVE based sample crucibles
    - Deltion Destin Drill w/ customized sample tubes

Vacuum Facility

VF13 at NASA Glenn Research Center

- Dedicated ‘dirty’ vacuum chamber
- Volume of 6.35 m^3
- 3.66m tall by 1.5 m diameter
- Temperature controlled cold wall
  - 2 Semi circular sections, independently controlled
  - Liquid nitrogen cooled
- Tailored electrical and mechanical feed through
- Additional Liquid Nitrogen supply for experiment (soil bin)
- Pressures O(10^{-6}) Torr



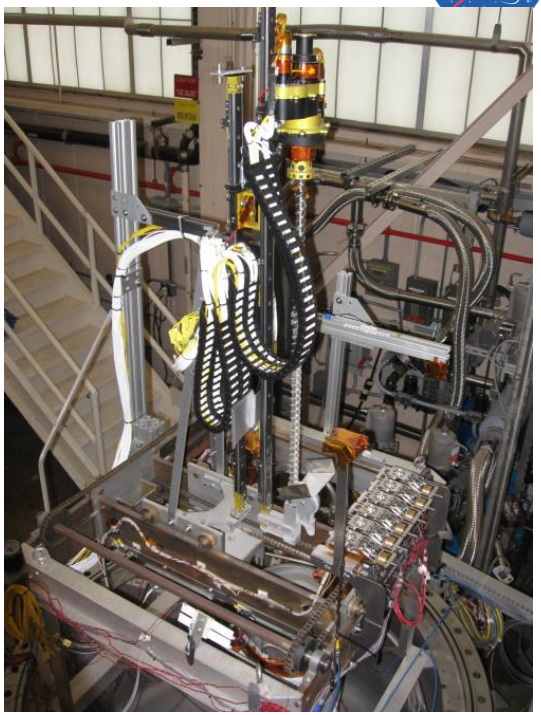


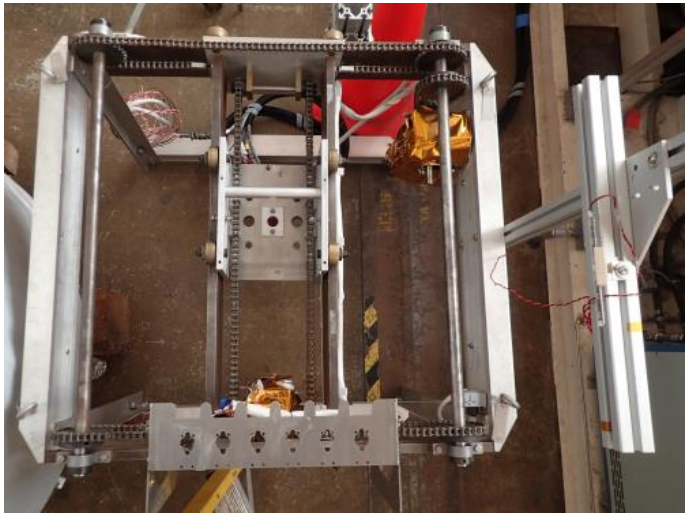
Simulant Bed

- Simulant bed sized to accommodate drill tests
  - 1.2m (48in) tall, 0.278m (11in) diameter
  - Holds 100 kg of simulant
  - Height to accommodate full 1m drill
  - Diameter for multiple drill holes
  - Wrapped with LN_2 coolant lines
  - Three side ports for soil embedded thermocouples (15, type T)
  - LHT-3m and Chenobi, doped with moisture

Hardware Platform

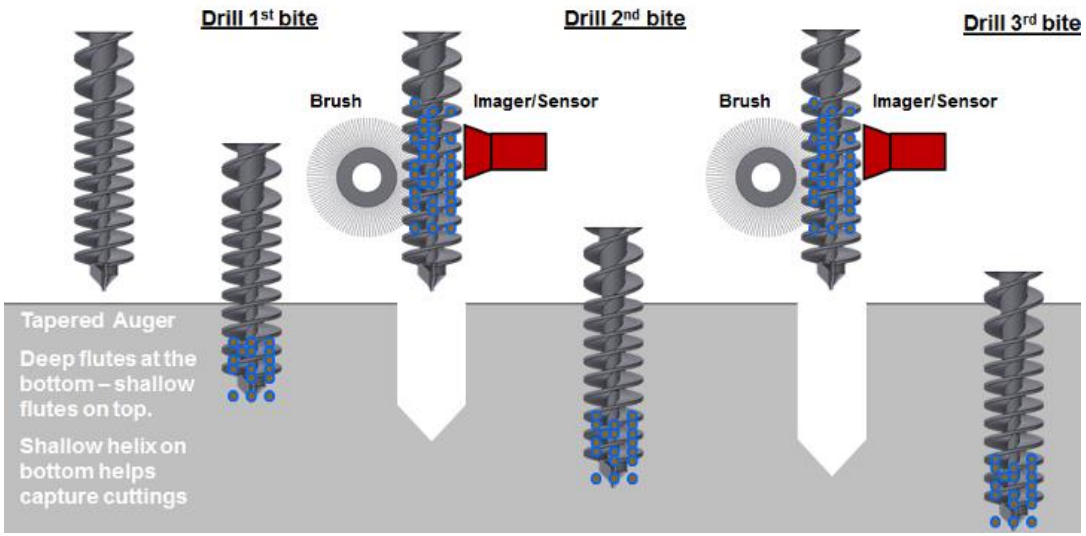
- 2D translation table for positioning over soil bed
  - Remotely actuated stepper motors and chain drives
  - Drill is mounted to the trolley which can be moved in two dimensions
  - Multiple drill holes per test
- 4 cameras and LED lights for test monitoring at vacuum
- Drill, SCMs, cameras all mounted to translation table





Lunar Prospector Drill- Honeybee Robotics

- Developed by Honeybee Robotics, and based on the Mars Icebreaker drill, TRL 5/6
- 100cm long, 2.5cm diameter auger
  - 10cm sample section has wider flutes at high pitch to capture granular material
  - Progressive ”Bite sampling” approach to drilling
    - Retains depth stratigraphy of the holes
    - Less material conveyed to surface, less chance of stuck bit
- Sample delivery mechanism
  - Deployed to surface as stabilizing foot
  - Fully contains the 10cm sample when auger retracted
  - Passive brush that rotates as auger spins past. Material brushed off auger and through funnel for collection
- Actuators: Percussion, deployment Z-stage, Drill Z-stage, Auger rotation



Lunar Prospector Drill- Honeybee Robotics

Hammer System

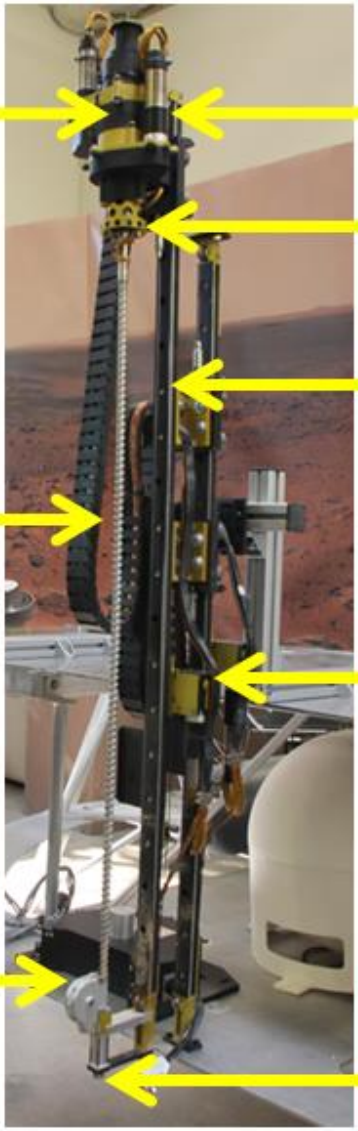
- 150 Watts
- 2-2.6 J/blow
- 2600 bpm
- Integrated in 8 different planetary drill systems

Auger

- Hollow: Enables wires for temp sensor to the bit
- Dual stage to enable sampling and auger cuttings to the surface.
- <25 mm diameter

Sample Delivery

1. Direct-to-Oven: Brush directly into a cup/oven



Rotary System

- Power: 150 Watt
- Rotation speed: 200 rpm
- Peak torque: 10 Nm

Slipring

- 4 channel
- Can support 1 RTD or 2 Thermocouples

Z-Stage

- Enables auger penetration to 1 m
- Pulley based
- Load from actuator current
- Max force: 500 N (any direction)

Deployment Stage

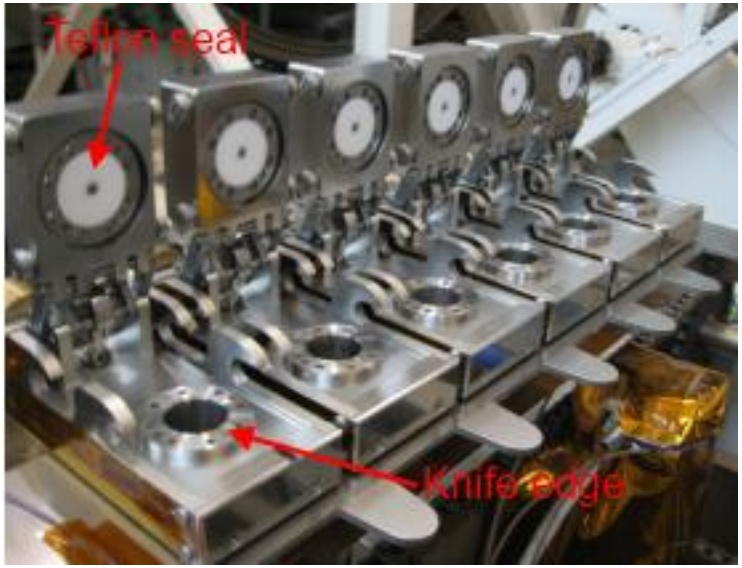
- Deploys and preloads drill against ground
- Pulley based
- Load from actuator current
- 40 cm stroke (depends on rover-ground clearance)
- Max force: 500 N (any direction)

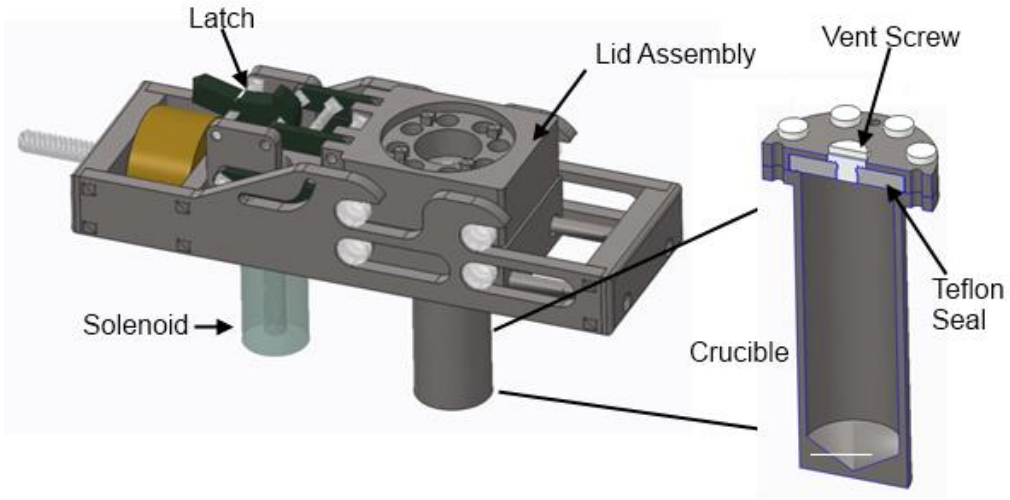
Bit

- Tungsten Carbide
- Serrated cutters
- Embedded temperature sensor

Sample Capture Mechanisms (SCM)

- Capture 10cc of soil from the auger and seal at vacuum conditions to retain volatiles
- Solenoid actuated, spring driven mechanism with a knife edge-to-teflon seal, 100lbf clamp force
- Sealed 18ml crucibles easily removed for sample analysis
- 6 Sample Capture Mechanisms in each test for multiple samples.





Honeybee Video of operation : drill & transfer

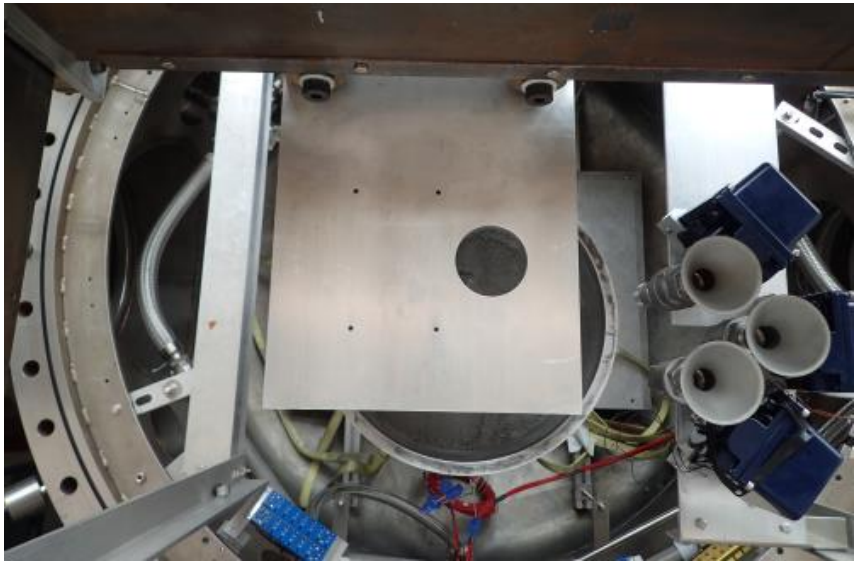
DESTIN VDCU Drill – Deltion Innovations

- Evolution of autonomous DESTIN 1m drill
- TRL 6: operation at 10-6 torr, 100K
- Tools for augering to 50cm, capturing 1 m contiguous consolidated core, or capturing 1m contiguous unconsolidated core
- Sample stratigraphy retained in core samples (coloured CHENOBI testing)
- Volatile retention in core samples
- Low power (<50Watts, including heaters for 1m sample, <40Watts to auger)
- Low thrust (nominal 100N)
- Core samples in frozen simulant at moisture concentrations from 0-5%, augering in 0-100%
- Bit temperature sensor in auger

Deltion Sample capture

Transfer Tube

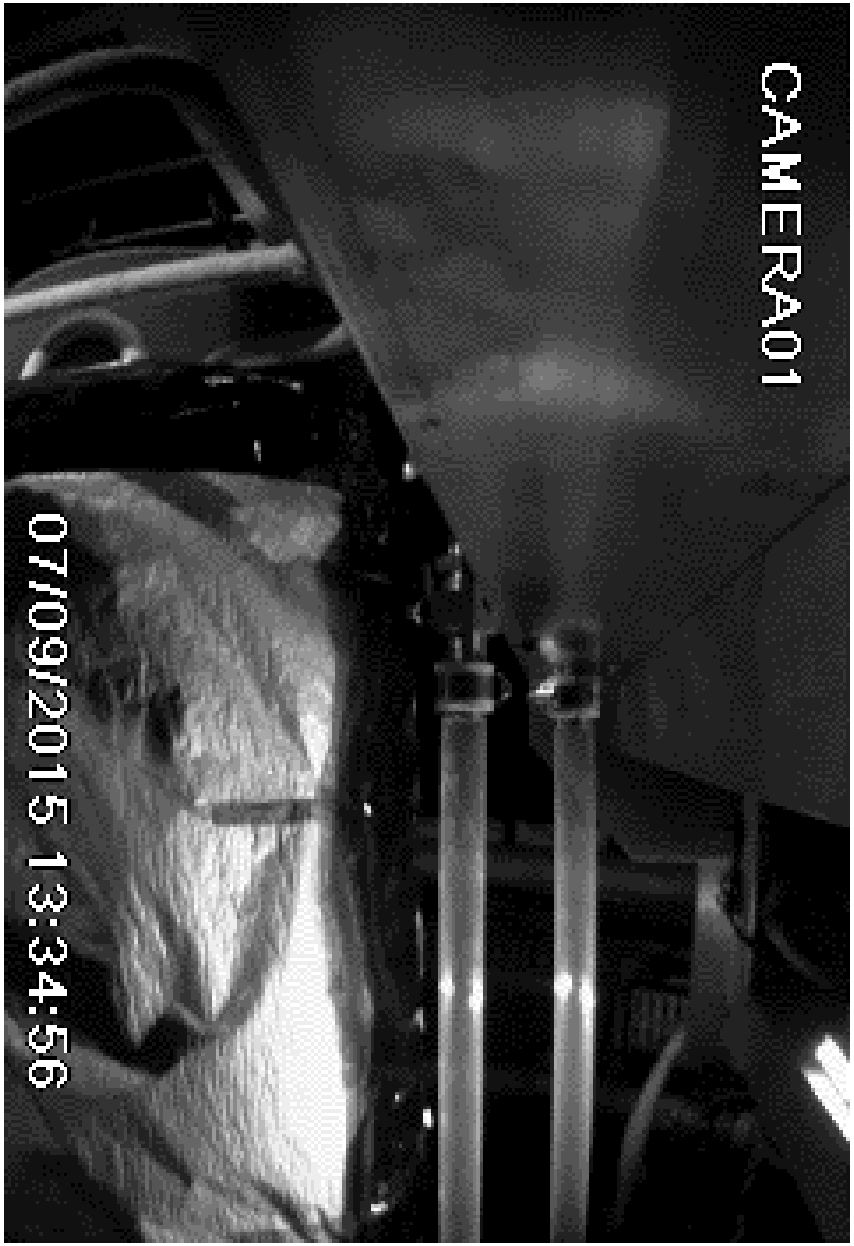
- Ball valve seal
- Teflon tubes:
  - 2ft long, 1in diameter
  - Folded w/ grease, and clamped with hosecock style clamp
- Tested on a leak checker to prove concept



Tool capture

- At the end of last drill hole, tool pressed into sheath to seal

Video of Transfer



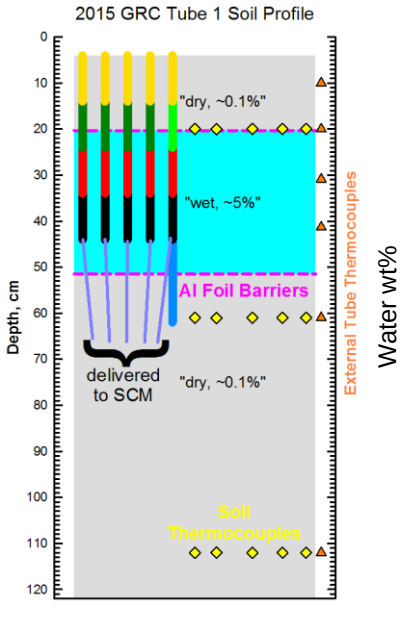
Test summary

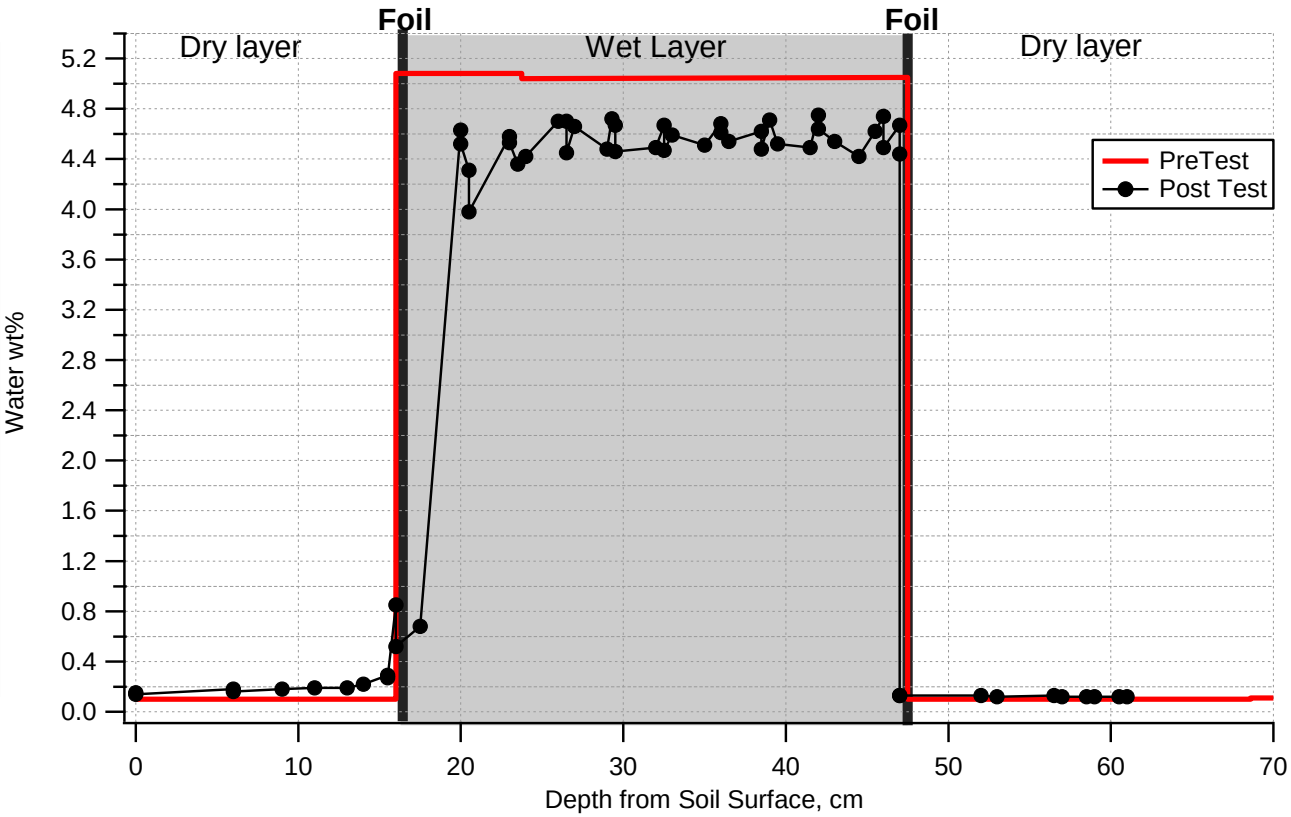
Test	Start Date	Test objective/ description	Soil Type	Soil Moisture	Lowest Vacuum, Torr	Shroud Temperature, °C	Avg soil temp (low), °C	Operations
Honeybee NIRVSS 1	3/5/2015	Volatiles loss and senstivity of NIRVSS. 5 sample capture crucibles	LHT	Stratified: room dry 5% room dry	5.E-06	-53	-80	5 holes to 40cm, 5 samples from 40cm
Honeybee NIRVSS 2	3/15/2015	Volatiles loss and senstivity of NIRVSS. 5 sample capture crucibles	LHT	Stratified: 0.5% 5% 0.5%	2.E-06	-175	-100	5 holes to 40cm, 5 samples from 40cm
Deltion 1, auger	6/22/2015	Auger w/telflon capture tubes x2 and tool capture	Chenobi	5%	1.E-06	-175	-115	3 holes to 50cm, 3 samples
Deltion 2, Core	6/29/2015	Core auger w/telflon capture tubes x2 and tool capture	Chenobi	reuse 5%	1.E-06	-175	-115	2 holes to 85cm, 2 samples
Deltion 3, Push	7/1/2015	Push tube w/telflon capture tubes x2 and tool capture	Chenobi	2%	1.E-06	-175	-112	1 hole to 25cm, 1 sample
Deltion 4, Core	7/8/2015	Core auger w/telflon capture tubes x2, and tool capture	Chenobi	reuse 2%	2.E-06	-175	-111	2 holes to 75+ cm 2 samples

Honeybee Test Matrix

DRILL TUBE 1 (Dry: 0.1%, Wet: 5%, Dry: 0.1%,)				
	Shroud Temp	Crucible Temp	Time to Seal	Bit Temp, C
Sample 1 – SCM 2, Crucible 2	- 50 C	Ambient	Fast as possible	-45
Sample 2 – SCM 4, Crucible 4	- 50 C	Ambient	Fast as possible	-45
Sample 3 – SCM 6, Crucible 6	- 50 C	Ambient	Fast as possible	-47
Sample 4 – SCM 3, Crucible 3	- 50 C	Ambient	~~3 minutes after transfer~~ Fast as possible	-48
Sample 5 – SCM 5, Crucible 5	- 50 C	Ambient	~~3 minutes after transfer~~ Fast as possible	-46
DRILL TUBE 2 (Dry: 0.5%, Wet: 5%, Dry: 0.5%,)				
	Shroud Temp	Crucible Temp	Time to Seal	
Sample 1 – SCM 2, Crucible 8	- 180 C	10 C	3 minutes after transfer	-68
Sample 2 – SCM 4, Crucible 10	- 180 C	10 C	3 minutes after transfer	-66
Sample 3 – SCM 6, Crucible 12	- 180 C	10 C	3 minutes after transfer	-64
Sample 4 – SCM 3, Crucible 9	- 180 C	10 C	3 minutes after transfer	-64
Sample 5 – SCM 5, Crucible 11	- 180 C	Ambient	3 minutes after transfer	-64

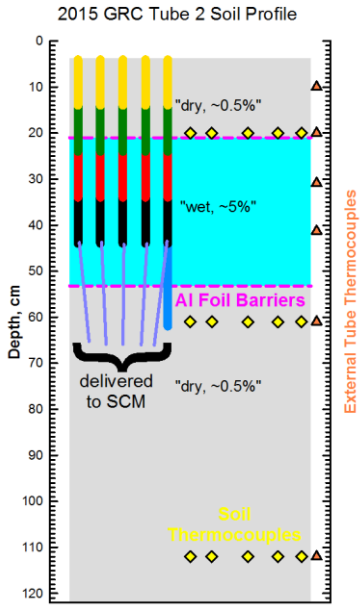
Test 1 – Soil Bin profile

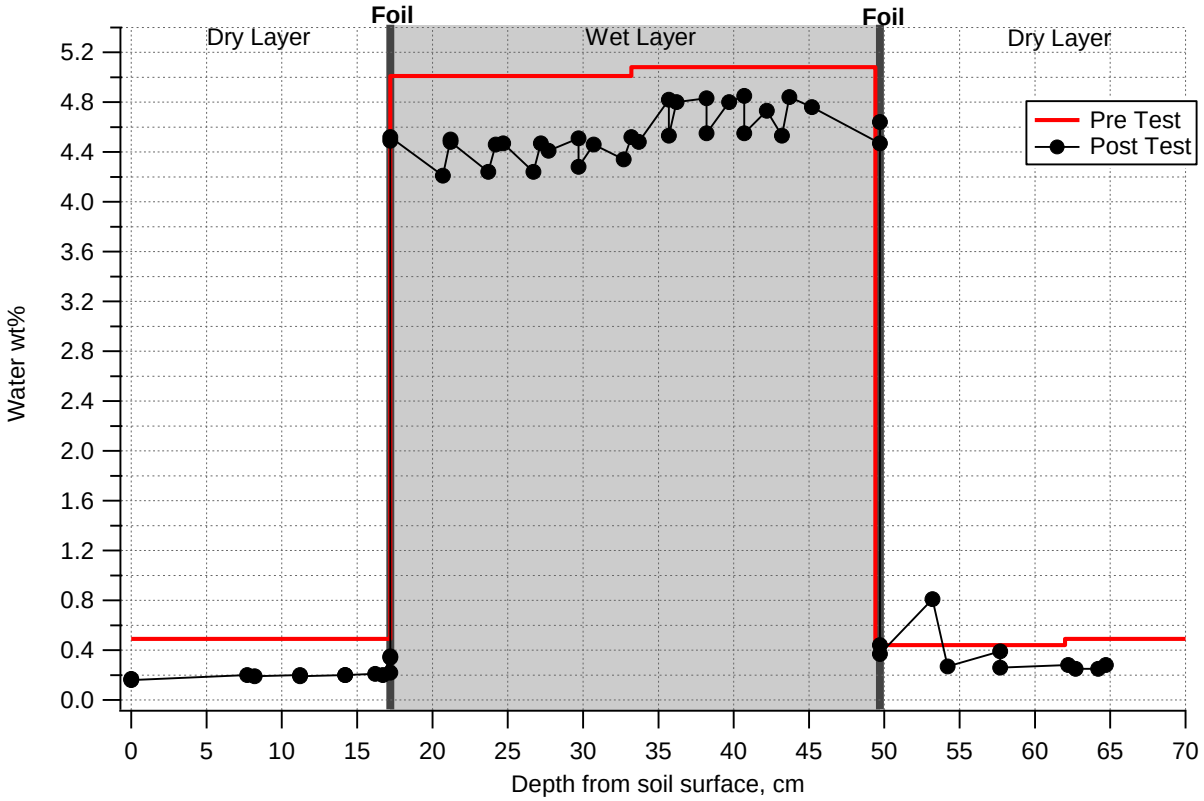




Note: Lower dry layer was not sampled to full depth (yet). Coring method does not work with dry soil, so ~60cm is as far as I can reach without dumping the bin.

Test 2 – Soil Bin profile



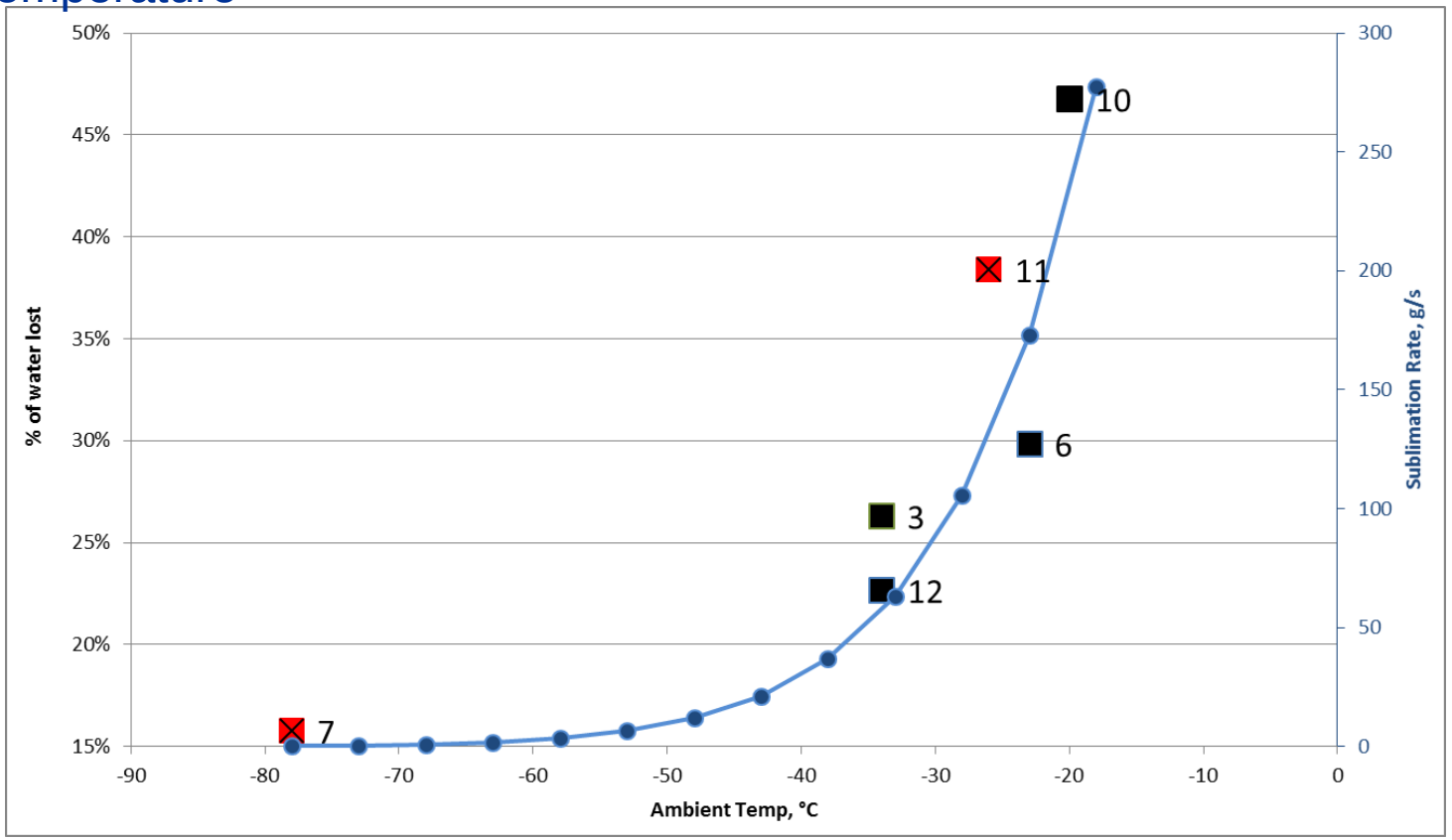


Note: Lower dry layer was not sampled to full depth (yet). Coring method does not work with dry soil, so ~60cm is as far as I can reach without dumping the bin.

Results from Honeybee sample capture

2014 test results, previously presented

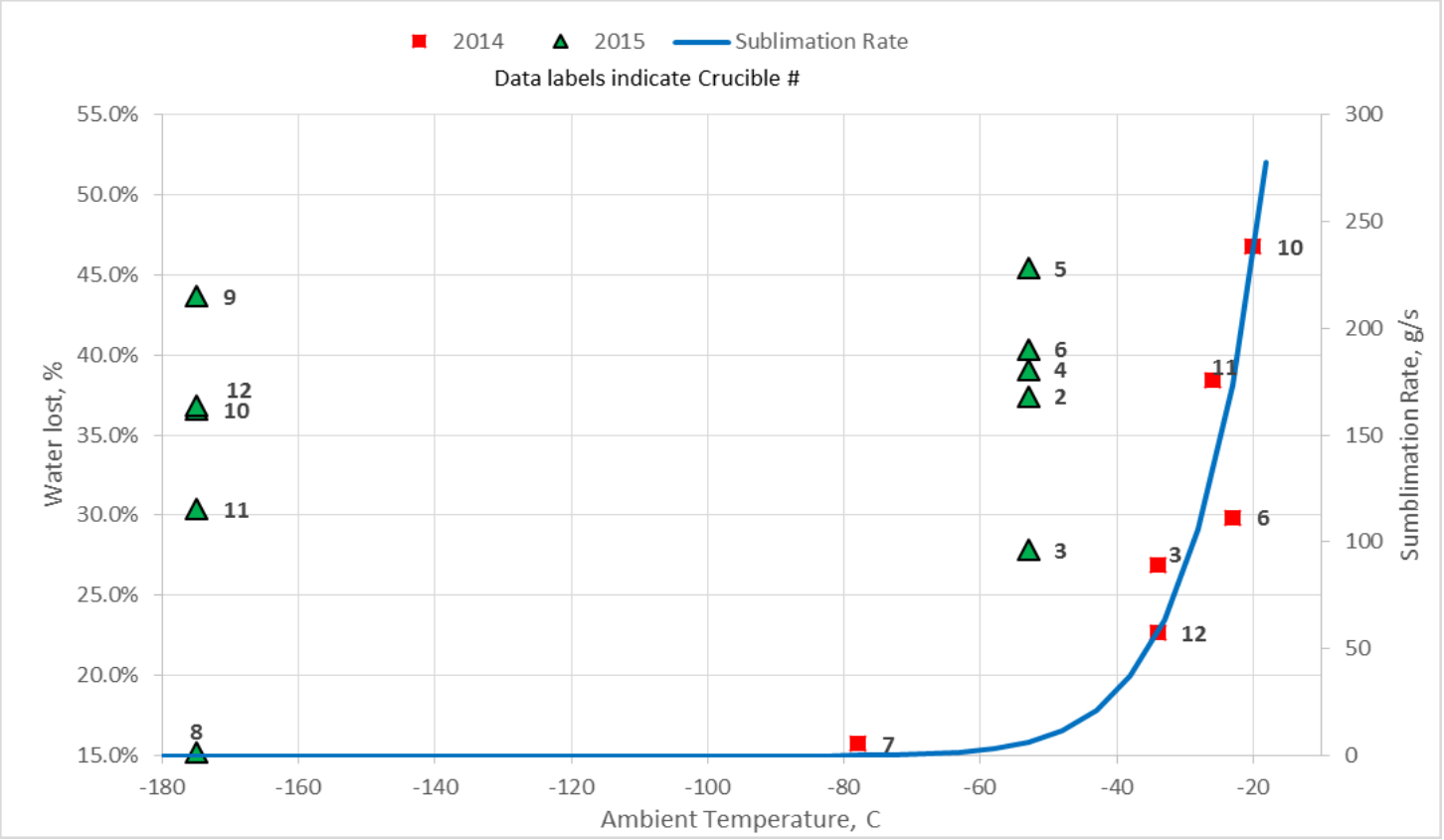
- Only well sealed sample captures are shown.
- Variables: Crucible exposure time, crucible temperature, ambient temperature



Sublimation rate from: Andreas, E., *New estimates for the sublimation rate for ice on the Moon*, Icarus, Volume 186, Issue 1, January 2007, Pages 24-30

Results from HB Auger capture

Moisture losses were in the same range as previous tests, but do not line up with sublimation curve.



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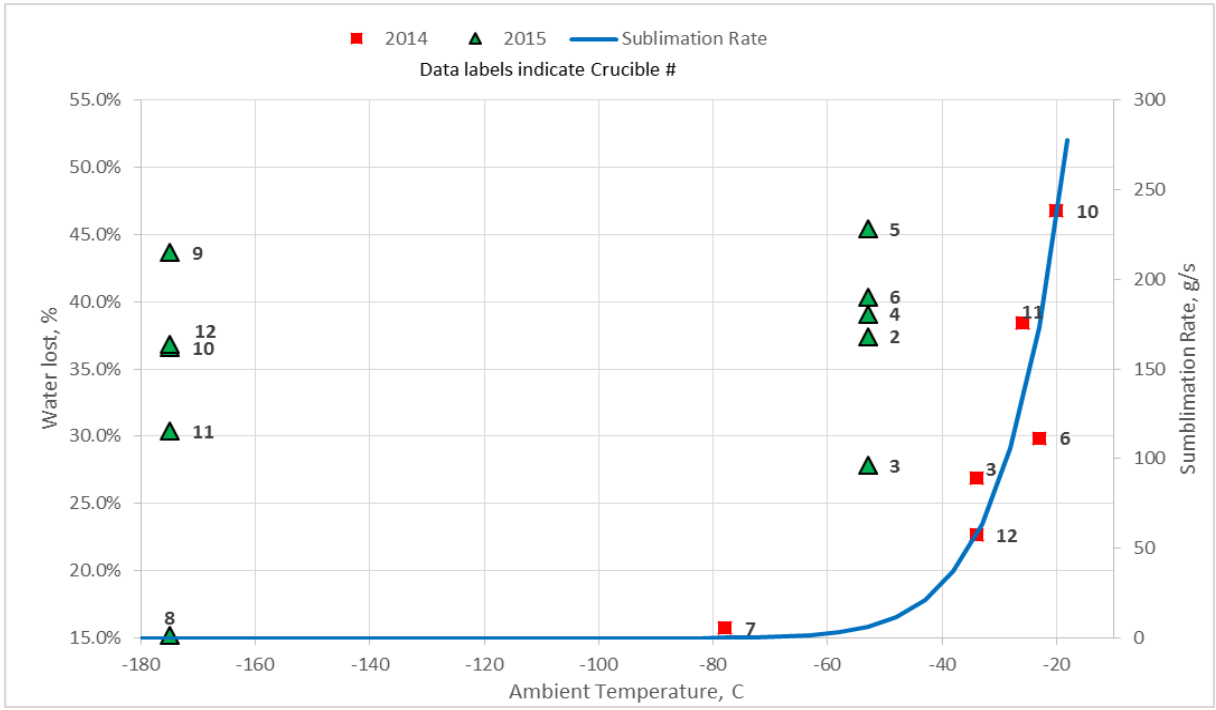
Results from Honeybee capture

Moisture losses in the same range as previous tests, but do not line up with sublimation curve. Potential variables influence:

- Stratified soil bin: step change in moisture content may have resulted in more cross contamination during drilling
- The holes were drilled using the bite approach, while the 2014 samples were straight drills.
- Potential residual dry sample material at brush spout
- The brush was exposed
- The NIRVSS lamp was on intermittently while sample was removed.
- Overall chamber pressure was lower than in previous tests



Deltion Test Matrix

DRILL TUBE 1 , 5%			
	Sample capture	Depth	Bit Temp at depth
Auger, Sample 1	Transfer Tube	50 cm	
Auger, Sample 2	Transfer Tube	50 cm	
Auger, Sample 3	Tool Capture	50 cm	
DRILL TUBE 1 , 5%, reuse			
Coring Auger, Sample 1	Transfer Tube	84.9 cm	
Coring Auger, Sample 2	Tool Capture	84.9 cm	
DRILL TUBE 2 , 2%			
Push Tube, sample 1	Tool Capture	25 cm	
DRILL TUBE 2 , 2% reuse			
Coring Auger, Sample 1	Transfer Tube	75 cm	
Coring Auger, Sample 2	Tool Capture	83 cm	

Results from Deltion Capture

- Results indicate water content over entire depth of hole. Only one sample was analyzed for stratification
- The tool capture method retained more moisture than the transfer tubes
  - Final sample (4 core tool capture) reused a capture mechanism not intended for reuse.
- The transfer process was not optimized for volatiles retention

Test, tool	Notes	Sample container	Soil prep	Wet soil mass, g	Dry Soil mass,g	Water mass	Water %, dry basis	% of availible water lost	Drill Depth, cm	Bit temp, C
1, auger		Transfer tube	5%	0.7	0.7	0.0	0.00%	100.0%	50	-72
1, auger		Transfer tube	5%	3.5	3.5	0.0	0.00%	100.0%	50	-85
1, auger		Tool capture	5%	14.8	14.7	0.1	0.68%	86.4%	50	-90
2, core		Transfer tube	5%	88.2	85.7	2.5	2.89%	42.1%	85	NA
2, core		Tool capture	5%	118.4	114.0	4.4	3.84%	23.3%	85	NA
3, Push tube		Tool capture	2%	65.7	65.6	0.1	0.22%	88.9%	25	NA
4, core		Transfer tube	2%	115.1	114.2	0.9	0.83%	58.7%	75	NA
4, core	SUMMED	Tool capture	2%	147.0	145.4	1.7	1.14%	42.8%	83	NA
4, core	bit end	(This sample was removed in sections to look at moisture distribution)	2%	20.0	19.9	0.1	0.46%	76.9%		
4, core	shaft 1		2%	22.2	21.9	0.3	1.42%	28.9%		
4, core	shaft 2		2%	54.8	54.0	0.8	1.50%	25.0%		
4, core	Bed surface		2%	50.0	49.6	0.5	0.91%	54.5%		

Results from Deltion Capture

- Auger tool: Not designed for sample capture. Little sample <15g captured from auger flights. Samples were dry, but sample tube seal was poor.
- Push Tube: One sample captured 65g. Logistical issues of sample transfer resulted in long exposure/possible poor seal. Sample lost 88% of its water
- Coring Auger: 4 samples averaging 115 g captured per hole. Water retention in same range as the Honeybee capture tests

Test, tool	Notes	Sample container	Soil prep	Wet soil mass, g	Dry Soil mass,g	Water mass	Water %, dry basis	% of availible water lost	Drill Depth, cm	Bit temp, C
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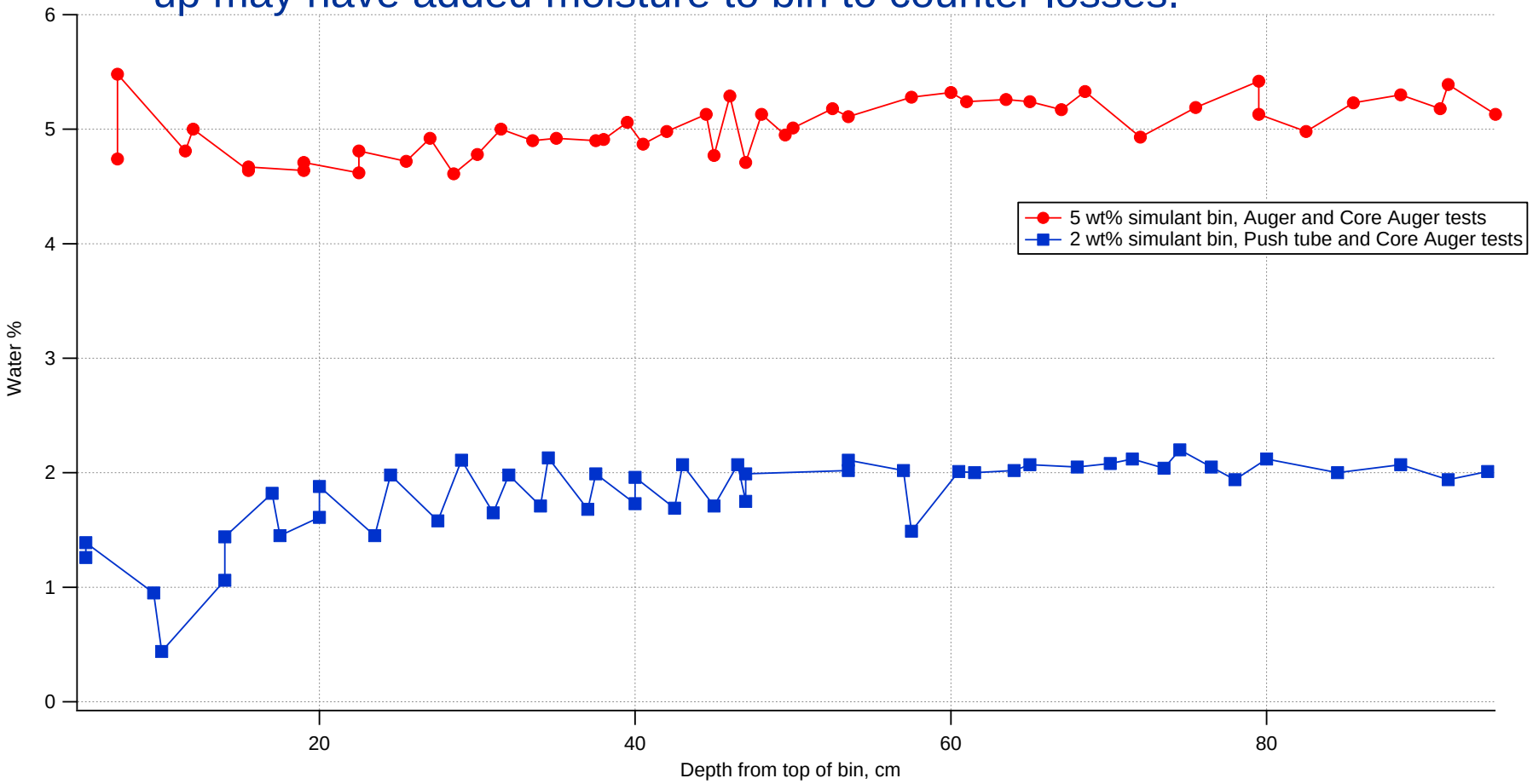
4, core	Bed surface		2%	50.0	49.6	0.5	0.91%	54.5%		

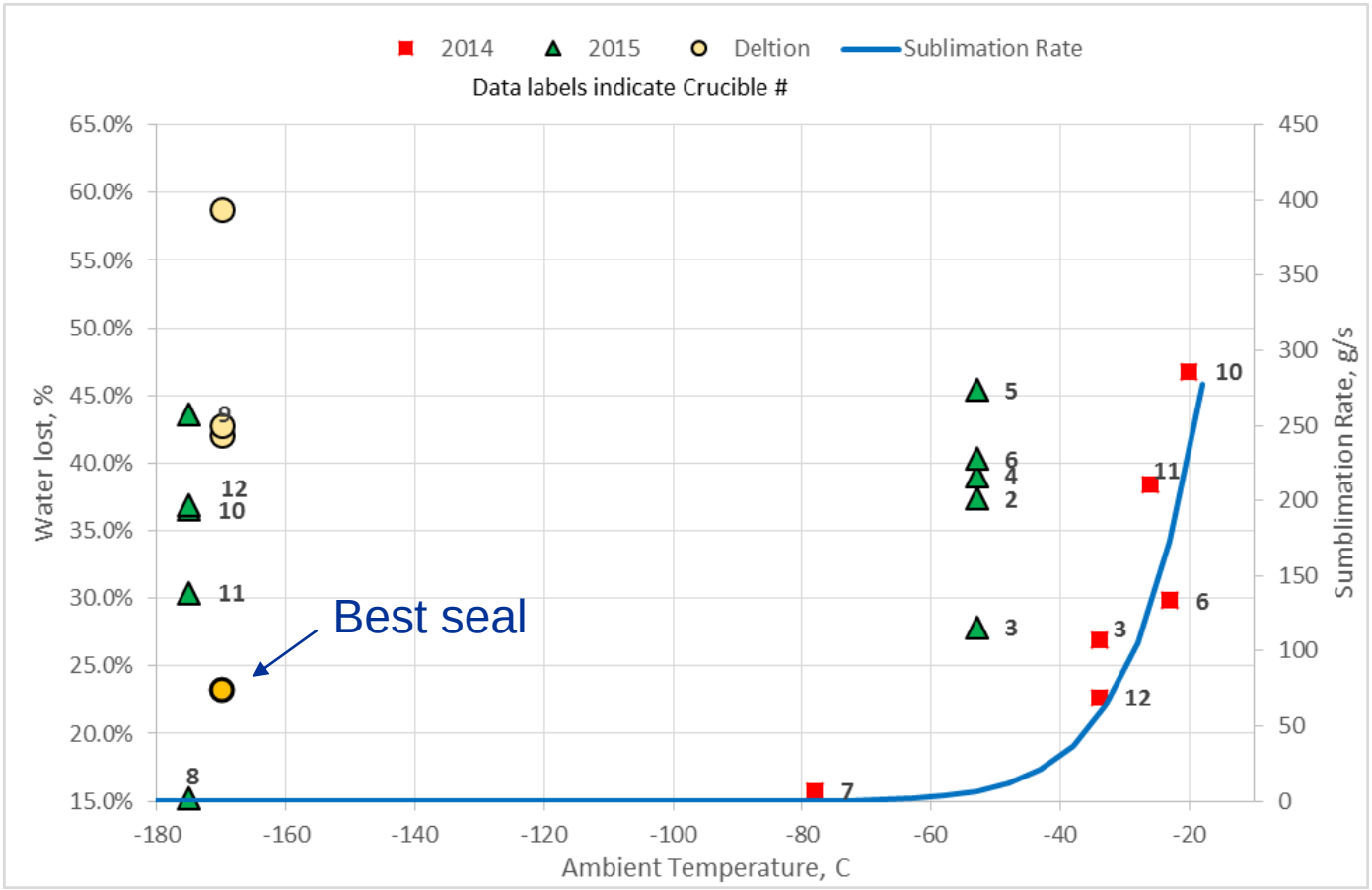
Post Mortem

- Despite reusing each simulant bed for multiple tests, the moisture content at the end showed little desiccation.
  - Conops: The bed was exposed to room air while still chilled, frost build up may have added moisture to bin to counter losses.



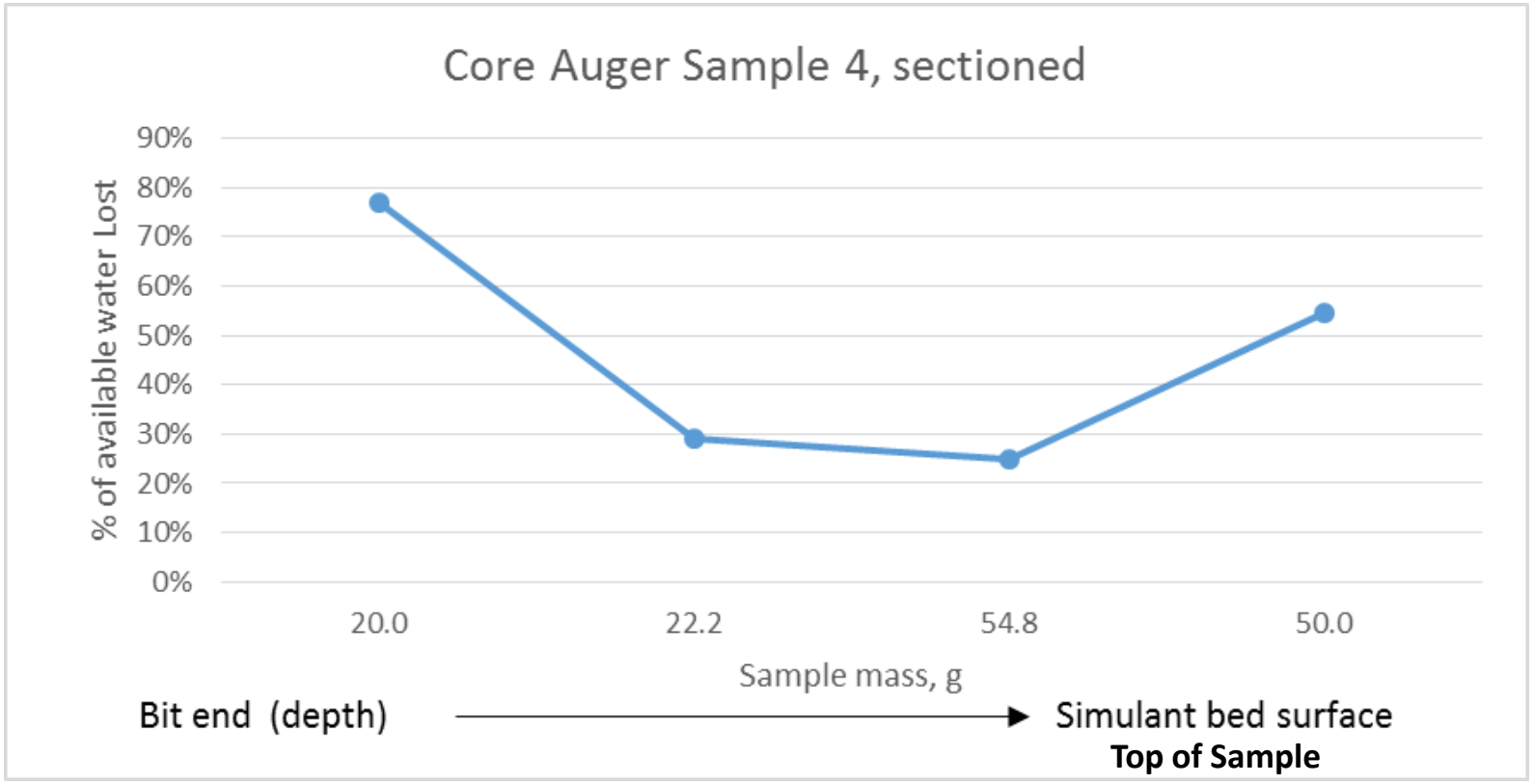
Results with Core Capture

- Core results
- Significantly more sample mass encompassing a broader depth, so average of drier surface layer and wetter soil at depth



Sectioned sample

- Exposed end of core auger shows water loss
- The center of the sample retained moisture more in line with predicted losses



Conclusions

- Previous data showed the volatile loss from augured samples was primarily a function of ambient environment conditions (exposure)
- Both of the new sampling results included new variables and configurations, so the data does not fall in line with previous results

  Auger sampling method
  - Stratified moisture content in soil bin, potential cross contamination from dry layers

  Core samples
  - Transfer tubes did not seal well, limiting data set
  - In tool sample capture retains more moisture overall
  - Non-uniform con-ops, different soil exposures
  - Larger sample sizes over broader depth so dry surface material in core combined with wet center: Retention of stratification not shown here
- Continued analysis of this data with new upcoming tests in 2016